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NEW LINAC TECHNOLOGY - FOR SSC, AND BEYOND?*

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Summary

With recent agreement on the high priority of seeking funding for a Superconducting Super Collider (SSC), it is appropriate to consider the injector linac requirements for such a machine. In so doing, the status of established technique and advantages of near-term R&D with relatively clear payoff are established, giving a base line for some speculation about linac possibilities even further in the future.

Introduction

At last year's Snowmass[1] and Oxford[2] meetings, attention focused on a next-generation very large hadron collider, and on possible limitations to achievement of very high energies. Preliminary outline of the collider envisioned a linac injector; the requirements and capabilities were elaborated further at the Cornell Workshop.[3] The initial questions were could the injector linac provide a beam of ~50 mA at 0.5-2.5 GeV with an output normalized emittance around 1π x 10^{-6} m·rad and output energy spread <0.1%, and how could its cost be minimized? It was felt that achieving the lowest possible emittance would strongly influence ring apertures.

As outlined below, we found that an essentially "conventional" linac could meet the output current, emittance, and energy-spread requirements. The Cornell Workshop realized that the low emittance would be of little advantage in the final, large ring because beam-beam interactions would be the determining factor in aperture size. However, it was pointed out by Y. Baconnier of CERN that if the emittance were kept low until the final spoiling in the big ring, it would have a very advantageous effect on the aperture requirement for the final booster ring--in fact, it would allow the same magnets to be used for that booster as for the main ring.

Basic SSC Injector-Linac Design

A negative-hydrogen-ion linac to deliver 50-μs pulses at a 1.0-Hz repetition rate would consist of an ion source, a radio-frequency quadrupole (RFQ) buncher/preaccelerator, a drift-tube linac (DTL), and a coupled-cavity linac (CCL).

Ion Source

Paul Allison (Los Alamos) estimates that the lowest emittance one might expect for a low duty factor, 70-mA, 100-keV, β = 0.0146, H^- ion source would be ~0.0275π mm·mrad rms, normalized. We used a "waterbag" distribution for simulation runs with total emittance equal to six times the rms. We would expect the source emittance to scale by roughly the square root of the current.

RFQ Linac

The RFQ is a revolutionary new type of accelerator for low-velocity ions and provides better capture, bunching, and initial acceleration of significant ion currents with less emittance growth than other methods. The current and emittance requirements strongly influence the operating frequency, chosen here as 440 MHz. All RFQ performance factors improve with higher electric field; the value 30 MV/m, which produces an electric quadrupole gradient of 0.84 MV/cm^2, was chosen from experience. The frequency scaling for allowable peak surface field is based on an ion-multipactoring model and empirical determination of constants known as the Kilpatrick Criterion:[4]

$$f = 1.643\ E^2 \exp -(8.5/E) \quad ;$$

the field E_{Kp} thus found is multiplied by a "bravery factor", K = 1.5 in this case, to determine the actual allowed peak surface field by accounting for the influence of modern techniques in raising the sparking limit. The resulting RFQ takes the beam from 100 keV to 2.5 MeV in 3.74 m; with 93% transmission giving 65 mA at the output; having normalized, rms transverse emittance of 0.085π mm·mrad; and longitudinal emittance containing 90% of the beam of ~0.45π deg·MeV, with ±30° phase spread and ±0.015-MeV energy spread.

Drift-Tube Linac

Transition is made to a DTL at the same frequency, 440 MHz, and peak surface field. In the context of the entire system, we studied the energy transition from DTL output to the subsequent high-beta CCL between 100-200 MeV. The overall cost increased about 10% over this range in transition energy; from longitudinal beam dynamics considerations, we chose 125 MeV for preliminary design. Constant length (2.54 cm), constant strength (18 kG/cm), permanent-magnet quadrupoles (PMQ) are used in the 200-cell, 40-m DTL. At 125 MeV, the transverse normalized, rms emittance is 0.125π mm·mrad, longitudinal emittance is 0.3π deg·MeV rms and 1.36π deg·MeV at the 90% contour, and transmission is 100%.

Coupled-Cavity Linac

The final energy for the linac injector could range from 0.5-2.5 GeV, depending on the booster design; in any case, the final CCL linac comprises most of the injector length and has a strong cost impact. Increased current limits and emittance damping allow this section to operate at a higher integer multiple frequency, 1320 MHz here, where components are smaller. The peak surface field at 1.5 E_{Kp} is 48 MV/m, but the accelerating field gradient chosen here is restricted, for reasons outlined below, to 8 MV/m. Transverse focusing is provided by a 6-kG/cm, 5.08-cm-long PMQ in a coupling cell after every 11 accelerating cells. A length of 425 m is needed to reach 2.5 GeV, where the transverse normalized rms emittance is 0.22π mm·mrad and over 50 mA is contained within the 90% contour of 1.0π mm·mrad. Transmission is 100%. Longitudinally, 90% of the output beam is within ±1.6° (at 1320 MHz) and ±0.5 MeV, with rms emittance of 0.18π deg·MeV.

Injector-Linac Costing and Important System Tradeoffs

Basic linac costs are given by

$$\mathrm{Cost} = R(P_{cu} + P_b) + SL + AC\,(\hat{P}_{cu} + \hat{P}_b) \quad .$$

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where R = cost/peak rf watt; P_{cu} = accelerator structure peak power due to losses; P_b = beam peak power; S = structure cost/unit length; L = accelerator length; AC = ac unit power cost; $\hat{P}_{cu}$ and $\hat{P}_b$ are structure and beam average power, equal to peak power times duty factor. The first two terms represent capital investment; the last term adds in the operating cost over the expected life. $P_{cu} = (E_0 L)^2/ZL = (\Delta W)^2/ZL$ where E_0 is accelerating gradient/unit length; Z is effective structure shunt impedance/unit length (includes transit time and synchronous phase-angle factors): and ΔW is the desired, fixed, particle-energy gain of the linac. $P_b = (\Delta W)$(beam current). Substitution shows the structure power cost varies inversely with length, whereas the structure cost varies directly with length. Therefore, there is a strong tradeoff between accelerating gradient and length, and choice of the maximum achievable accelerating gradient is not a priori desirable. Ignoring the operating cost, differentiation with respect to length yields the optimum length and thus gradient for lowest cost:

$E_{c\,opt} = (SZ/R)^{1/2}$, independent of ΔW;

$L_{opt} = \Delta W(R/SZ)^{1/2}$;

$C_{opt} = \Delta W[2(SR/Z)^{1/2} + RI]$, linear in ΔW.

At the optimum, $RP_{cu} = SL$. Folding in operating cost will push the optimum E_0 down and optimum L up.

CCL Structure Efficiency

We need to examine the cost equation further to see more of the influencing factors. It is reasonable to expect that we would want to exploit the accelerator structure to some physical limit, even though the cost relation warns us to be careful. The applicable physical limit will depend on the application and could be, for example, removal of average waste power, voltage breakdown, surface damage due to high peak power, magnetic field limitations, space-charge limit on current, and so on. The SSC injector-linac beam-current requirements, pulse length, and duty-factor considerations essentially fix the operating frequency near the 440 MHz/1320 MHz chosen; in this frequency range a limiting factor comes from the electric field sparking limit as defined by the Kilpatrick Limit (KL) above (20 MV/m at 440 MHz, 32 MV/m at 1320 MHz). The experience factor $K = E/E_{KP}$, by which E_{KP} may be multiplied for modern structures, appears to be as high as 2.5-3.0 for RFQs, and up to 2.0 for DTL and SSC structures. Thus, for our 1320-MHz CCL, we can consider peak surface fields of up to about 54 MV/m.

All the peak surface field, however, cannot be used for acceleration--geometry factors in practical structures reduce the effective gradient on-axis by some factor. This factor can be minimized but usually at some cost, for example in shunt impedance Z or transit-time factor, which would directly offset the increased accelerating gradient, E_0. For example, one structure with many desirable properties is called the disk-and-washer (DAW) type (Fig. 1). The addition of noses around the beam hole increases the transit-time factor, at some loss in shunt impedance, and increases the peak-surface-field to accelerating-field ratio (E/E_0) from 1.94 with no nose to 5.37 with full nose. The Vaguine structure has a somewhat better efficiency in using peak surface field as accelerating field, with the Chalk River structure intermediate.

The fabrication cost/unit length, S, of all these structures is rough!, the same, \$50-100 K/m. The tradeoffs among shunt impedance (~50-100 MΩ/m), transit time (0.8-0.92), and other detailed factors are also not dramatic. Therefore the gradient vs

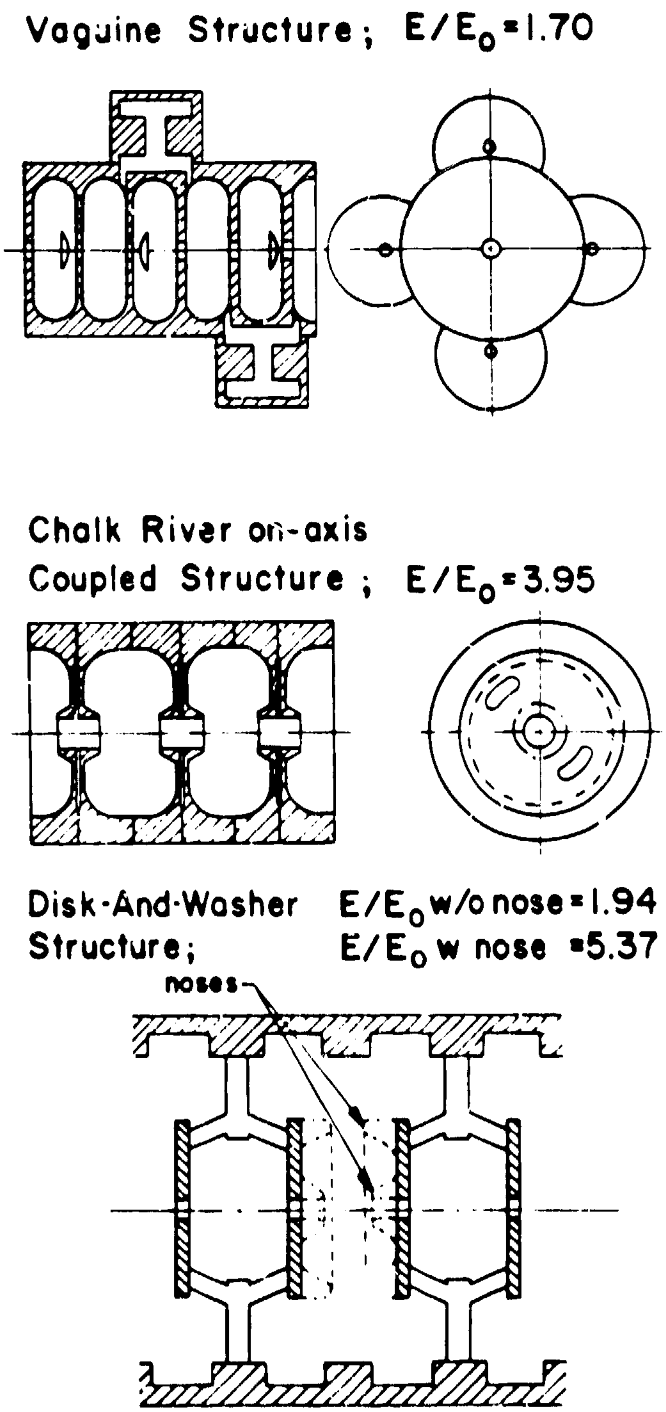

Fig. 1. Cross-sections of four CCL types: the DAW with and without nose, the Chalk River on-axis coupled structure[3] and the Vaguine structure.[4] E/E_0 is ratio of peak surface field to accelerating gradient.

length cost tradeoff must dominate the choice of optimum gradient. Figure 2 illustrates this result, showing the cost curves and relating E, E_{KP}, and E_0 for the four structures. The cost minima are all at about \$20 M and require an accelerating gradient of ~20 MeV/m. The available E_0 (30-40 MeV/m) at K = 2 of the more efficient structures cannot be economically

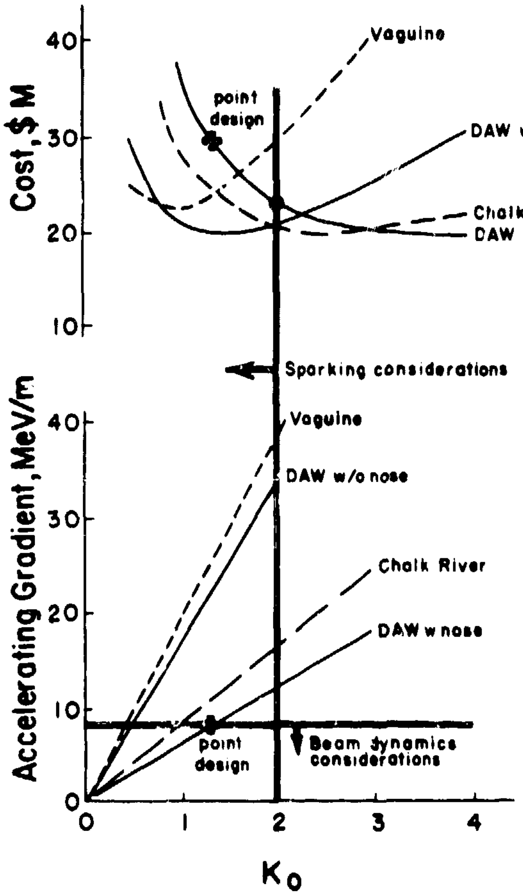

Fig. 2. Cost estimate for the SSC 2.5-GeV injector linac as a function of K, the ratio of peak-surface-field E in the CCL accelerating structure to the Kilpatrick limit E_{KP} = 32 MV/m at 1320 MHz, and the CCL accelerating gradient E_0 as function of K. Curves for the four CCL geometries of Fig. 1 are plotted.

used, but the 20 MV/m E_0 giving the cost minimum is available below the sparking limit. The less efficient structures cannot reach the cost minimum without sparking, although this is not too serious because the cost minima are broad. Another look at the cost equation shows the optimum $E_0 \propto (SZ/R)^{1/2}$; thus, we could use a higher accelerating gradient if we could get the effective structure shunt impedance up or the unit rf power cost down.

A great deal of rf accelerating structure development has occurred at frequencies $\leq$3 GHz, and it is unlikely that major increases in shunt impedance will occur. Also, as with structure cost, the cost per peak rf watt at low duty factor is relatively independent of frequency in this frequency range, at about $0.01-0.015/watt. The quoted costs are for all source or structure components ready to connect to utilities and building. The rf source building costs are probably somewhat lower than the structure building costs, so this would push the optimum gradient up somewhat.

Emittance Growth

If 40-MV/m accelerating gradient is available for the CCL, but we can only use half that for economic reasons, why did we limit the SSC injector point design by more than another factor of 2, to 8 MV/m? The CCL and DTL accelerating gradients were assumed fixed throughout; this is the common practice. The transverse emittance growths through the DTL and CCL were 1.47 and 1.76. Much of this growth is because the beam from the preceding stage has not been properly conditioned for minimum emittance growth in the next stage. We know[7] that the transverse and longitudinal phase-space energy contents must be kept roughly equal (termed equipartitioned) at all stages of an accelerator or transients will occur in the particle distribution that force emittance transfer between planes until equipartitioning occurs. In typical linacs, the longitudinal phase-space energy is larger than the transverse, and the transverse emittance grows, especially when an abrupt change in parameters excites new transients. The very high accelerating gradients suggested by the cost optimization would exacerbate the emittance growth considerably if we injected directly into the CCL at those gradients. The longitudinal emittance would also deteriorate from the effect of rf waveform nonlinearities. To realize the desired transverse emittance and energy spread for the point design, we limited the CCL accelerating gradient to 8 MV/m. Even then, the equipartitioning condition is badly violated and considerable emittance growth occurs in the transverse plane. The cost impact of operating at this nonoptimum gradient is significant.

Research into how to maintain equipartitioning through a linac is just starting--obviously it is an important area for further work. We do know what the matching and equipartitioning conditions are for the rms beam parameters, and have some knowledge of parameter space to avoid if minimum emittance growth is desired. One clear requirement is that the beam must be handled gently, with gradual deformations to a new state. We might be able to use the optimum 20 MeV/m gradient for a substantial fraction of the CCL by injecting at a low gradient and gradually shaping the acceleration parameters to bring the gradient up to 20 MeV/m. We know just enough at this point to know that the proper prescriptions are not obvious.

Synopsis of SSC Injector Linac

We have shown that an appropriate linac could be built using conventional techniques. The optimum cost is a tradeoff between accelerating gradient and length. The cost would be higher than optimum because the need to bound emittance growth forces us to choose a below-optimum accelerating gradient. The maximum accelerating gradient achievable is about twice the optimum; thus, the possibility for a shorter machine cannot be economically exploited. It is probable that R&D on linac design that maintains equipartitioning would yield more cost-effective designs and even better performance. Utilization of the achievable structure gradients probably requires work on reducing the cost per rf watt.

Future Linacs, and Whither High Gradient?

Particle accelerators, and perhaps linacs particularly, using electrons, protons, and a wide range of ions, are being applied more and more to practical applications as well as research tools. The best machine for each job will vary as much as the applications do; but the need of high-energy physics for extremely high-energy particles, with enough luminosity at the same time to conduct experiments, brings most of the issues into focus. Recently, several entire meetings[1,7,8] have been devoted to exploring ultimate performance, and a number of excellent review papers have been written[9-11] on the general problem and various aspects of the supporting technology. I will not presume to rederive or even to review all of this work here, but will borrow freely, especially from M. Tigner (Cornell) and D. Prosnitz (LLNL), in order to add a few remarks to the subject.

In particular, in looking at the SSC injector possibilities where achievable high accelerating gradients are not usable, I became interested in whether the idea of super-high gradient (100s to 1000 MeV/m), and therefore short linacs, really make any sense economically. In at least one scenario, outlined by Prosnitz[12] and sketched out below, matters appear promising.

Beam Loading

The linac costing equation indicates that it would be desirable to have the beam power dominate the structure power. However, intense bunches extract energy directly from the stored energy in the system, and generate wake fields that affect the following particles. The maximum allowable beam power[9] to stored rf power ratio therefore is only about 10%.

Boyd[13] has shown how a stagger-tuning concept might significantly enhance the achievable charge transfer through a linac operating in a stored-energy mode. Each bunch would pass through cavities or blocks of cavities operating at different synchronous phases achieved by phase modulation of two separate rf sources, or by operating the sources at slightly different frequencies and injecting the particles when the beat has the proper phase relationship. Without consideration of wake-field effects, he shows that a radiographic machine could produce an order of magnitude more bremsstrahlung flux by using this technique to transfer more charge within the specified emittance and energy-spread requirements.

Gluckstern, Cooper, and Channell[14] recently have extended the wake-field analysis to include the effects of coupling between accelerating cells and external focusing, and to elucidate the transient and steady-state conditions.

An amalgamation of these considerations is now needed, and would be an important consideration, for example, in the machine scenario outlined below.

Frequency Scaling

In Fig. 3, the possible limits to accelerating gradient, for a structure with peak-surface-field to accelerating gradient ratio of 2, are diagrammed. The

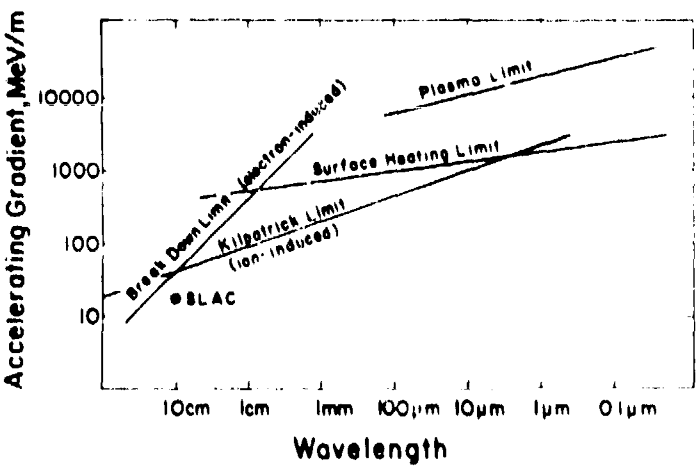

Fig. 3. Approximate limits on accelerating gradient, for structures with assumed ratio of peak surface field to accelerating gradient equal to two, vs wavelength. Kilpatrick limit-line also assumes peak surface field of twice KL.

Kilpatrick-limit line, which scales as $f^{1/2}$, has been added to the electron-induced breakdown and surface-heating limits derived by Tigner and Prosnitz.[9] A frequency around 30 GHz may be at about the point of diminishing returns, and gradients of a few hundred MeV/m may be possible. We assume that beam-dynamics consideration would allow their use.

In loaded waveguide structures, shunt impedance Z scales as $f^{1/2}$ and, if we use $E \propto f^{1/2}$, the structure power required would stay relatively constant, while the structure cost term in the cost equation would decrease. The cost, length, and gradient optima scale as $f^{\pm 1/4}$, which is not very fast.

As noted above, structure cost does not seem to vary much with frequency, running about \$50-100 K/m. Evidently, as we decided above, the cost per rf watt would have to be significantly reduced to enable the economical use of high accelerating gradient.

As outlined by Prosnitz,[12] rf generators are being developed for high power at high frequencies, but there are disadvantages in that many of these devices are oscillators, rather than amplifiers in which amplitude and frequency or phase can be controlled, and many require high magnetic fields that add to the cost. Reliability also is not adequate yet. At high gradient, the amount of power required per meter is very high, although at high frequency, the amount of energy needed per meter is dramatically reduced, because $E^2 \propto \omega^2 U$. Tube-type sources can produce relevant unit power/m at 10 GHz, but not yet at 30 GHz, where paralleling would be needed. Given these uncertainties, I have not tried to estimate the \$/rf watt cost for these drivers, but imagine that it would still be $\sim$\$0.01/rf watt. In this case, high accelerating gradient would not be economical.

Two-Beam Accelerator

Prosnitz goes on to outline a scenario that, although a very formidable physics and engineering challenge, appears quite remarkable upon reflection.

The proposed linac would accelerate 5×10^{10} particles per bunch to 300 GeV at 1-kHz repetition rate in a 35-GHz, π/3-mode, jungle-gym-type structure with Z = 210 MΩ/m, Q = 2.6×10^3, operating at 200-MeV/m accelerating gradient. The rf power requirement is 235 MW/m, but only 12 J/m with 50-ns pulses.

The driver would use a low-voltage (1.8 MeV) but high-current (500-A) electron beam and would convert its energy to 35 GHz rf, using distributed wigglers in a single-pass free-electron-laser (FEL) source/amplifier. FEL wiggler and induction-linac sections would be alternated so that the electron beam energy lost in a wiggler section (decelerating gradient 1.6 MeV/m) would be made up in the next induction-linac section. With 1.8-MeV/m equilibrium beam voltage and 350-A bunched current, it is estimated that 570 MW/m of rf could be produced. The conversion efficiency is estimated to be very high, $\geq$70%, which is better than klystrons, especially high-peak-power klystrons, at 3 GHz and below. The rf is used to drive the high-voltage, low-current accelerated beam, so that the entire system is like a transformer.

Induction-linac and permanent-magnet wiggler structure costs are probably conservatively estimated in the same \$50-100 K/m range as the rf structures; therefore, one crude estimate of the cost per rf watt is (\$50 K/m)/(235 MV/m) = 2×10^{-4} \$/rf watt. Another crude estimate is to use the \$50 M construction budget for the 50-MeV, 10-kA ATA at Lawrence Livermore National Laboratory, which implies 1×10^{-4} \$/rf watt. A more detailed estimate by Prosnitz,[12] indicates 1.2×10^{-3} \$/rf watt. Because induction-linac costs scale with the joules (volt•s) required, the low current here, compared to ATA, penalizes the power cost.

If it can be realized, this is indeed the kind of cost reduction needed to reduce the total cost of accelerating a small number of particles to very high energies and to make the use of very high gradients economical. Discounting the costs to \$100 K/m and 5×10^{-4} \$/rf watt would imply reductions in the optimum cost terms of $(20)^{1/2}$ and (20) compared to $R = 10^{-2}$ \$/rf watt, and an optimum accelerating gradient of $\mathcal{E}_{0\ opt} = [(10^5)(210 \times 10^6)/(5 \times 10^{-4})]^{1/2} = 200$ MeV/m.

Conclusion

For at least this possible two-beam accelerator FEL-accelerator, the rude introduction of economics does not spoil the picture, but indicates that, as in the past, innovation might still significantly affect the achievement of even higher energy particle beams of sufficient luminosity. In particular, at least this approach (because it provides low-cost rf), would allow high accelerating gradients in the several hundred MeV/m range to be economically used.

Acknowledgments

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